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Contributions to the

XXVII Plenary Meeting of COSPAR

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Abstract: This report contains preprints of three papers presented at the XXVII Plenary Meeting of the Committee on Space Research (COSPAR):

1. Radiation Hazards on Space Missions Outside the Magnetosphere, by J.R. Letaw, R. Silberberg and C.H. Tsao

2. Model Analysis of Space Shuttle Dosimetry Data, by J.R. Letaw, R. Silberberg, C.H. Tsao and E.V. Benton

3. Galactic Cosmic Rays and Cell-Hit Frequencies Outside the Magnetosphere, by S.B. Curtis and J.R. Letaw

The conference was held 18-29 July 1988 in Helsinki, Finland. The final versions of these papers will be published in Advances in Space Research with the conference proceedings.

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RADIATION HAZARDS ON SPACE MISSIONS OUTSIDE THE MAGNETOSPHERE[1]

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ABSTRACT

Future space missions outside the magnetosphere will subject astronauts to a hostile and unfamiliar radiation environment. An annual dose equivalent to the blood-forming organs (BFOs) of ~50 cSv is expected, mostly from heavy ions in the galactic cosmic radiation. On long-duration missions, an anomalously-large solar energetic particle event may occur. Such an event can expose astronauts to up to ~25 Gy (skin dose) and up to ~2 Sv (BFO dose). The anticipated radiation exposure may necessitate spacecraft design concessions and some restriction of mission activities. In this paper we discuss our model calculations of radiation doses in several exo-magnetospheric environments. Specific radiation shielding strategies are discussed. A new calculation of aluminum equivalents of potential spacecraft shielding materials demonstrates the importance of low-atomic-mass species for protection from galactic cosmic radiation.

[1] Paper Identification No. XIX.2.2. This manuscript was invited for presentation at the XXVII Plenary Meeting of the Committee on Space Research (COSPAR), Helsinki, Finland, 18-29 July 1988.

INTRODUCTION

Planning for future space missions outside the Earth's magnetosphere has been initiated /1/. The establishment of permanently manned bases on the Moon and exploratory manned missions to Mars are receiving increasing support from policy makers /2/ and citizen groups. These exciting developments have stimulated us to assess the radiation hazards on future missions in order to (i) determine whether the missions are feasible and (ii) recommend strategies for protecting the astronauts from adverse effects.

Proposed missions outside the magnetosphere will thrust astronauts into a hostile and unfamiliar space radiation environment. The environment consists of highly-penetrating galactic cosmic radiation (GCR) with occasional activity from solar particle events (SPEs). Astronauts in the 28.5° inclination Space Shuttle orbits receive no significant exposure from either of these radiation components. The Earth's magnetic field forms an effective shield which deflects most charged particles from equatorial regions.

The proposed missions require significantly longer periods outside the magnetosphere than previous missions. For example, a round trip flight to Mars requires approximately 2 years plus additional time for exploration in orbit around and on the surface of Mars. This may be compared with about 2 weeks for lunar explorations of the Apollo era. The expected doses, and hence the consequences of these exposures, are dramatically increased by the longer duration.

Galactic cosmic radiation consists of protons and heavy ions with energies per nucleon in the range 100 MeV to 10 GeV. These particles have been observed on space flights outside the magnetosphere with plastic-track detectors /3/ and as light flashes in the astronaut's eyes /4/. Astronauts have never been subjected to long-term ($\geq$ 1 year) exposure from GCR heavy ions. The assessment of radiation effects from heavy ions is difficult because there is little epidemiological data available from terrestrial sources.

Solar energetic particle events are a more familiar concern on missions outside the magnetosphere. However, with the advent of long-duration missions, an anomalously-large SPE may occur with a probability of 25% to

50% /5/ (a three-year mission has been assumed). We feel that an anomalously-large SPE should be considered a "likely event" rather than a "remote possibility" by mission planners. In assessing the risks from such an event we have used the August, 1972 event as a model because it is the best-measured and most-intense SPE known. Use of other models leads to significantly different risk assessments.

TRANSPORT MODEL

The radiation dose calculations presented here were performed using the transport code, UPROP /6/, and the most recent CREME GCR environment model /7/. The codes provide a prediction of the fluxes, LET spectra, and radiation doses from cosmic-ray heavy ions ($1 \leq Z \leq 28$) over energies per nucleon in the range 1 MeV $\leq E \leq$ 100 GeV. Calculations are performed on a 500 point logarithmically-spaced energy grid.

The transport code provides an exact numerical solution of the one-dimensional continuity equation taking into account both ionization losses and nuclear fragments. Ionization losses are treated in the continuous slowing down approximation. Nuclear fragmentation processes are treated in the straight-ahead approximation which assumes that fragments maintain the same velocity as their progenitors after a nuclear interaction. All orders of fragments (secondaries, tertiaries, etc.) are followed in the calculation.

The UPROP code has been validated by comparison with two other transport codes which were written independently and use different numerical methods. The first of these codes /8/ does not follow nuclear fragments and uses different fragmentation mean free paths and ionization loss rates from UPROP. The radiation doses from GCR at solar minimum behind 1 g cm^{-2} aluminum shielding using these codes are within 3%. The dose equivalents (using conventional quality factors) are within 4%.

The second code /9/ uses numerical derivatives to solve the transport equation. It has been applied to GCR transport in an early calculation by our group /10/. Using the code UPROP we have repeated that calculation taking into account differences in quality factor and environmental model from our present procedure. At the center of a 5 g cm^{-2} spherical shell of water we compute annual doses of 9.1 rad and 30.2 rem, to be compared with 9.2 rad and 31 rem in Ref. 10 indicating excellent agreement between codes. It is of interest to note that our present calculations of these quantities are 11.6 rad and 48.6 rem, respectively. The doses have increased as a result of changes in quality factor and environment model.

The CREME GCR environmental model has been compared with spaceflight dosimetry data from Apollo and Skylab missions /11/. Model LET spectra were within a factor of 2 or 3 of measured LET spectra. A number of factors were not treated fully in that comparison, including actual shielding distributions around the dosimeters and the limitations of plastic-track detector response. Work is currently underway to explore these factors.

RADIATION ASSESSMENT METHODOLOGY

In this paper, estimates of the risk from ionizing particle radiation are performed using conventional radiation protection practice. The dose in water is obtained from an LET (linear energy transfer) spectrum computed by the transport code and is used as an estimate of the tissue dose. The dose equivalent /12/ is obtained using the quality factors recommended by the ICRP (International Commission on Radiological Protection) /13/. Dose equivalent provides a better correlation with long-term, stochastic effects than dose. Other approaches to space radiation protection may be useful; one such approach based on particle fluences is considered in an accompanying paper /14/.

Two methodologies for evaluating the risks of a given radiation exposure are used here. The first, and most fundamental, is to assess the risk that radiation exposure will endanger the completion of a mission by disabling the astronauts. The second is to verify that radiation dose equivalents are within legislated limits and as low as reasonably achievable.

Potential short-term health problems of space radiation exposure /15/ include erythema (ED_{10} = 400 cGy, ED_{50} = 575 cGy), prodromal sequelae (ED_{10} = 40-90 cGy, ED_{50} = 100-240 cGy), and hematological depression (ED_{10} = 50-80 cGy, ED_{50} = 120-190 cGy). Each of these effects is manifested within a week or two of exposure. The impact of these health effects on the crew depends on the number of astronauts affected and the degree of discomfort or incapacitation. Death from radiation, 2 to 8 weeks after exposure, occurs with LD_{10} = 220 cGy and LD_{50} = 285 cGy.

Long-term incidence of cancer is the guiding factor in NASA radiation protection guidelines. These guidelines are currently under study by a committee of the NCRP (U.S. National Commission on Radiation Protection and Measurement) /16/. The Committee has recommended monthly, annual and career dose limits to the skin, eye lens, and bone marrow for male and female astronauts. Limits for the bone marrow are based on a 3% lifetime excess risk of *death* from cancer. Monthly and annual limits for the bone marrow are 25 cSv and 50 cSv.

The NCRP radiation guidelines were designed specifically for application on the Space Station. It is not yet clear whether these guidelines will become a *de facto* standard for all spaceflights. Furthermore, the guidelines are subject to change as new data, for example, the reassessment of doses to A-bomb survivors /17/, become available.

It is noteworthy that NCRP limit of 50 cSv yr^{-1} to the BFOs is 10 times greater than the maximum allowance for terrestrial radiation workers, and 100 times greater than allowed for the general population. Typical whole body exposure from natural background radiation in the U.S. is ~0.1 cSv yr^{-1} /18/.

RADIATION RISKS

The radiation dose equivalent as a function of aluminum shielding depth has been calculated and is shown in Figure 1. The dose has been evaluated at zero tissue depth (skin dose). The maximum skin dose from GCR at solar minimum is about 75 cSv yr^{-1} for shielding of 1 g cm^{-2}. For thinner shielding the GCR model is uncertain because of great variability in the low-energy components. The BFO dose may be estimated by adding 10 g cm^{-2} to the shielding thickness. The maximum BFO dose from GCR at solar minimum is about 50 cSv yr^{-1}.

Four components of the dose are shown. The primary protons and heavy ions (i.e., cosmic rays which have not suffered nuclear interactions) constitute most of the dose for thin shielding. Fragments are reaction products of the GCR which have undergone nuclear interactions. Fragments are a relatively minor constituent of the total dose. Target secondaries are protons, alpha particles, and heavy recoil nuclei which have been accelerated from rest in the target material by primary cosmic rays and their reaction products. Neutrons with energy < 20 MeV are another target secondary, but have required a different computer code for their estimation /19/. A quality factor of 20 was used for low-energy neutrons.

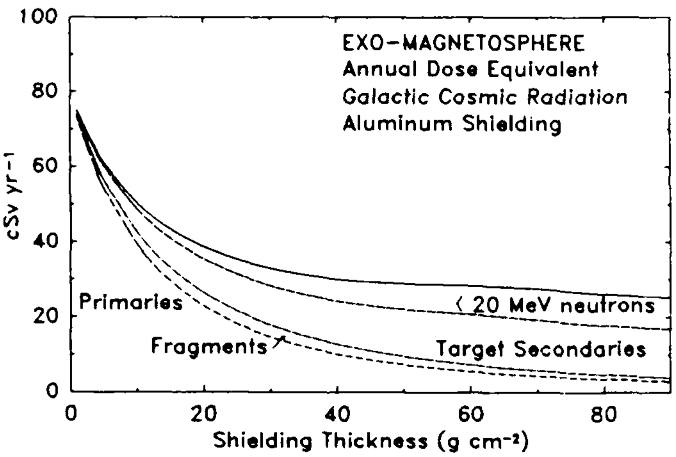

Figure 1: Annual dose equivalent from galactic cosmic radiation at zero tissue depth as a function of aluminum shielding thickness.

We note that accurate estimation of the fragment contribution to the total dose requires many nucleus-nucleus cross sections which are unmeasured. It is of interest that the fragment contribution is at most ~10% in our calculations. Relatively large errors in the cross sections can therefore have only a minor effect on the estimate of total dose from GCR. Uncertainties in the radiation environment, biological effects of heavy ions, and dosimetry present more urgent concerns.

Figure 2 shows a decomposition of the GCR primary and fragment dose according to charge. Iron makes up approximately 25% of the dose equivalent. Other important species are silicon, magnesium, neon, oxygen, carbon, helium, and protons. The contribution to dose equivalent is strongly weighted toward the higher-charged cosmic ray species, rather than those which are

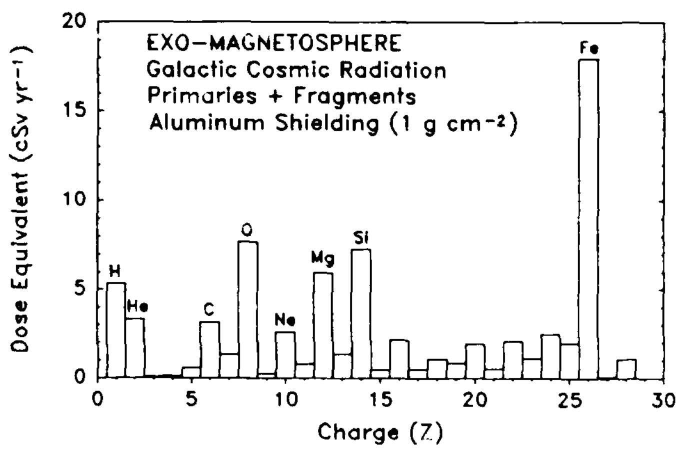

Figure 2: Elemental contributions to the dose equivalent from galactic cosmic radiation at solar minimum after passage through 1 g cm^{-2} of aluminum shielding.

most abundant. This results from a combination of the Z^2 dependence of LET and a quality factor of up to 20 for heavy ions.

Radiation doses for the August, 1972 anomalously-large SPE are shown in Figure 3. Two calculations have been performed. The first /20/ shows the dose equivalent to the BFOs as a function of aluminum shielding thickness. This computation is useful in evaluating the contribution of the SPE to the monthly BFO limits proposed by the NCRP. The second calculation shows the skin dose as a function of aluminum shielding thickness. This computation is useful for determining the shielding required to prevent early effects of radiation.

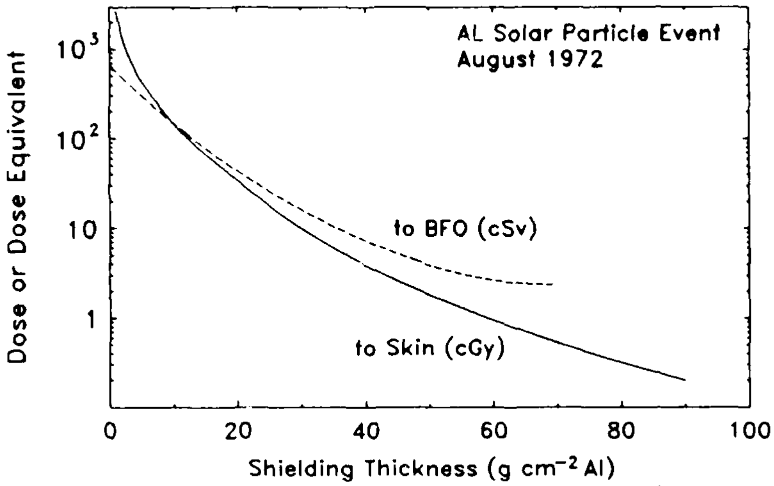

Figure 3: Dose equivalent to the blood-forming organs and skin dose as a function of aluminum shielding thickness for the August, 1972 anomalously-large solar energetic particle event.

SHIELDING CONSIDERATIONS

Requirements for shielding from the anomalously-large SPE may be derived from Figure 3. Early skin effects (erythema) are an important consideration with doses above 400 cGy. This threshold is exceeded when the shielding thickness is < 5 g cm^{-2} for a 4π steradian exposure or < 3 g cm^{-2} for a 2π steradian exposure. When astronauts are shielded by less than these amounts, early skin effects are a concern.

Other early effects (prodromal sequelae, hematological depression) occur as a result of whole body doses. They are important when doses exceed 50 cGy. If we assume the body provides self-shielding approximately equal to 10 g cm^{-2} of aluminum, then the threshold for these effects is 7 g cm^{-2} of aluminum shielding. With the same assumption, the maximum whole-body dose for the August, 1972 event is ~150 cGy, which is below the threshold for lethality, LD_{10}.

Astronauts can be protected from the early effects of an acute exposure to radiation from a SPE with a storm shelter having > 7 g cm^{-2} aluminum shielding or its equivalent over 4π steradians. We feel that such a shelter should be mandatory on all long-duration missions outside the magnetosphere because of the large probability of a SPE. This shelter insures that the mission will not be jeopardized by a SPE of the same magnitude as the August, 1972 event.

Solar particle events also contribute to the monthly, annual and career radiation doses of the astronauts. Astronaut doses must be limited to within legislated limits, which may be similar to the NCRP guidelines. In addition, the doses must be minimized in accordance with the ALARA (as low as reasonably achievable) principle. If it is required that the monthly BFO dose must never exceed 25 cSv, then (according to Figure 3) a storm shelter providing 25 g cm^{-2} (~9 cm) of aluminum shielding is required. If the legislated limit is 50 cSv, then 19 g cm^{-2} (~7 cm) of aluminum shielding is required. Such limits can impose extraordinary mass requirements on a long-duration mission.

Requirements for shielding from GCR may be derived from Figure 1 and the NCRP radiation dose guidelines. Once again the legislated guidelines, which restrict the number of excess cancer deaths due to space radiation and not the risk of early effects, are the source of these requirements. With 10 g cm^{-2} of body self-shielding, the annual dose equivalent is about 50 cSv. This corresponds exactly to the annual limit to the BFOs recommended by the NCRP. No additional shielding is required to match the NCRP monthly and annual guidelines. Age- and sex-dependent career limits may restrict the length of a mission, or the sex or minimum age of participating astronauts.

If mission planners wish to apply a safety factor of 2 to the GCR dose limit to account for the multitude of uncertainties in this dose assessment, then no practical amount of aluminum shielding can offer enough protection to the astronauts. In Figure 1, the radiation dose remains above 25 cGy to beyond 30 cm of aluminum. This shielding would be required for all habitable parts of the spacecraft.

Since aluminum shielding is inadequate to provide a significant reduction in the GCR dose, we have investigated the radiation dose from several other shielding materials. Our choices include: (a) aluminum, the typical structural material of spacecraft, (b) copper, about equivalent to iron, another common spacecraft material, (c) water, a requirement for life-support systems, (d) hydrogen, a common spacecraft fuel, (e) lead, a useful material for shielding from gamma rays, and (f) methane, a hydrogen-rich material which may also serve as a fuel. Radiation dose equivalent versus shielding thickness for these materials is shown in Figure 4.

We note immediately the extraordinary difference in attenuation of galactic cosmic radiation by these six materials. Hydrogen, with the lowest atomic mass, provides by far the best shielding of GCR. Lead, with the greatest atomic mass of the group, is the worst of the shields.

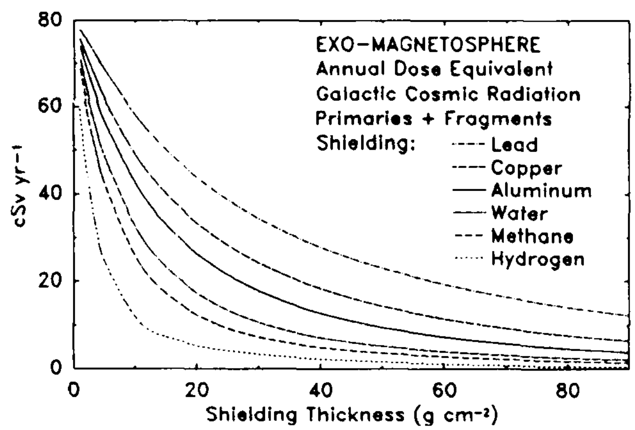

Figure 4: Annual dose equivalent from galactic cosmic radiation as a function of shielding thickness for several possible spacecraft shielding materials.

The differences in shielding properties stem from two factors. First, the nuclear fragmentation cross sections on different target materials increase roughly as the square of the radius of the target nucleus ($A^{2/3}$). On the other hand, the target mass increases as A. Hence, per unit mass, lower mass materials offer more surface cross section for nuclear fragmentation. The second effect is the ionization losses which increase roughly as the number of electrons (Z) available in the material. Once again, the mass increases as A, which grows faster than Z because of neutrons. Hence, lighter materials provide more electrons per unit mass and are more effective at slowing heavy ions. (A third factor, production of secondary neutrons, also favors light nuclei which are relatively neutron poor.)

From Figure 4 we have derived a formula for estimating the aluminum shielding equivalent (X) of any thickness, x g cm^{-2}, of another material having mean atomic mass, $\bar{A}$. Thus,

$$X = 3.19\, x^{.977 + .041 \ln \bar{A}}\, \bar{A}^{-.371}$$

for $\bar{A} > 1$ and

$$X = 4.35\, x^{.966}$$

for $\bar{A} = 1$ (hydrogen). This formula represents our data to within 10% for shielding in the range $0.5 \text{ g cm}^{-2} \leq x \leq 80 \text{ g cm}^{-2}$.

For rough estimates, the equivalent aluminum shielding for any thickness of H, CH_4, H_2O, Cu(Fe) or Pb may be obtained by multiplying by 4.35, 2.07, 1.64, .684 or .441, respectively. Thus liquid hydrogen shielding is equivalent in effect to 4.35 times its weight (or thickness in g cm^{-2}) of aluminum. Approximately 50% more iron (nearly the same in effect as copper) than aluminum is required to produce the same level of radiation protection.

ADDITIONAL ENVIRONMENTAL FACTORS

Other factors pertinent to the assessment of radiation risks on missions outside the magnetosphere have been discussed in previous reports. We review these factors briefly here.

A typical interplanetary mission will involve three exo-magnetospheric phases. During the interplanetary phase, the spacecraft is exposed to unattenuated particle fluxes from GCR and SPEs. There is no safe haven so all protection must be provided within the spacecraft.

During the orbital phase, the spacecraft is close to the planet. It is protected from some (< 50%) of space radiation by the "shadow" of the planet. The transmission factor for space radiation is given by $(1 + \cos\Theta)/2$ where $\sin\Theta = R_{Planet}/R_{Orbit}$. It is possible that a safe haven on the planetary surface could be reached within a matter of hours.

During the surface phase, the astronaut is fully shielded from 50% of space radiation by the "shadow" of the planet. The annual BFO dose from GCR on the Moon is therefore about 25 cSv. Additional shielding may be provided by the atmosphere of the planet. For example, the atmosphere of Mars has about 1% of the pressure of the Earth's atmosphere or 10 g cm^{-2}. This is sufficient to reduce the radiation dose by an additional factor of two (from the dose on the lunar surface) to about 12 cSv yr^{-1} /21/.

Permanent or emergency radiation protection on planetary surfaces may be obtained underground. About 2 m of lunar soil is required to bring the annual dose equivalent down to 0.5 cSv, the limit for terrestrial radiation workers /22/. 5 m to 10 m of lunar soil is required to reach natural terrestrial radiation levels.

SUMMARY

An assessment of radiation doses and shielding requirements for exo-magnetospheric space missions has been presented. We find that lethal radiation doses are not expected from anomalously-large solar particle events as intense as the August, 1972 event. The onset of early radiation effects from a SPE is prevented by supplying a storm shelter having > 7 g cm^{-2} aluminum shielding on all sides. Legislated radiation exposure limits, based on future incidence of death from cancer, can increase the required storm shelter shielding to as much as 25 g cm^{-2}.

Galactic cosmic radiation doses are within NCRP monthly and annual guidelines. No additional shielding is required to protect the astronauts. Age and sex of participating crew members may be restricted by career dose limits depending on the length of the mission. If a safety factor of 2 is required, then it is practically impossible to supply the necessary aluminum shielding. Other shielding materials are available and have been considered.

Hydrogen (liquid or gaseous) is equivalent in shielding effect to 4.35 times its mass in aluminum for shielding GCR. It is the ultimate GCR shielding material. Methane, water, copper (iron), and lead are equivalent to 2.07, 1.64, 0.684 and 0.441 times their mass in aluminum, respectively. Similar factors apply for shielding of protons from SPEs.

We find that missions outside the magnetosphere are feasible. There is a high probability of an anomalously-large SPE which must be planned for. A storm shelter having at least 7 g cm^{-2} of aluminum shielding should be mandatory on all long-duration exo-magnetospheric missions. Additional shielding may be required to insure that long-term cancer incidence is held below acceptable limits.

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MODEL ANALYSIS OF SPACE SHUTTLE DOSIMETRY DATA[1]

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ABSTRACT

An extensive model analysis of plastic track detector measurements of high-LET particles on the Space Shuttle has been performed. Three shuttle flights: STS-51F (low-altitude, high-inclination), STS-51J (high-altitude, low-inclination), and STS-61C (low-altitude, low-inclination) are considered. The model includes contributions from trapped protons and galactic cosmic radiation, as well as target secondary particles. Target secondaries, expected to be of importance in thickly shielded space environments, are a significant component of the measured LET (linear energy transfer) spectra.

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INTRODUCTION

The high-LET particle environment on manned space missions has been monitored since the Gemini era /1/. Measurements have been undertaken using lexan polycarbonate, cellulose nitrate, and CR-39 plastic track detectors which record the passage of high-LET particles within certain bounds of LET, range, and incidence angle. Due to the restricted efficiency of this measurement technique, it is necessary to use additional dosimetry and model calculations to determine the radiation dose at the measurement site.

The purpose of the present work is to compare a complete model calculation of the LET spectra within astronaut personnel dosimeters with observations. This comparison provides validation of particle transport and space radiation environment models in the presence of the complexities of realistic circumstances. We attempt a more comprehensive test than has been performed in the past /2/, /3/ by including primary contributions from both trapped protons and galactic cosmic radiation, and all secondary components. The comparison also allows the importance of target secondary contributions /4/ to the radiation dose to be verified. Secondary contributions have been identified as a major obstacle to shielding from galactic cosmic radiation on long-duration space missions /5/. Finally, an estimate of the actual radiation dose (and dose equivalent) at the site of the dosimeter can be provided.

For this calculation we have chosen to work with measurements from three Space Shuttle flights. STS-51F (Challenger) flew on 29 July 1985 for 191 hr in a 322 × 304 km orbit at 49.5° inclination. STS-51J (Atlantis) flew on 3 October 1985 for 95 hr in a 510 km, 28.5° inclination orbit. STS-61C (Columbia) flew on 12 January 1986 for 146 hr in a 324 km, 28.5° orbit. These flights span the range of radiation environments so far experienced in low-Earth orbit /6/. Low-altitude (~300 km) flights are subject to much less intense trapped proton radiation than high-altitude (~500 km) flights. Low-inclination (~30°) flights are better protected from galactic cosmic radiation than high-inclination (~60°) flights. The selected flights took place during a broad solar minimum (mid-1985 through mid-1986) where environmental models are well defined.

CALCULATIONAL PROCEDURE

The following components of the radiation environment are expected. The list below is arranged so that the number of levels of indenture indicates the *minimum* number of interactions needed to develop that component. First level (primary) particles generate ionization losses directly. At least one nuclear interaction is required to generate the second level and two interactions are needed to generate the third level. "Secondary" in this list refers to second and all higher order interaction products. Material for all secondaries except GCR fragments originate in the target. In general, one expects fluxes from the first level to exceed those from the second, which exceed those from the third level, because of the large interaction mean free path of ions in materials such as aluminum and water.

1. Trapped protons	1.1 Secondary protons	1.1.1. Recoil nuclei ($2 \leq Z \leq 9$)
	1.2 Secondary neutrons	1.2.1 Recoil nuclei
	1.3 Recoil nuclei	
	1.4 Other secondaries (π, γ, etc.)	
2. GCR protons	2.1 Secondary protons	2.1.1 Recoil nuclei
	2.2 Secondary neutrons	2.2.1 Recoil nuclei
	2.3 Recoil nuclei	
	2.4 Other secondaries (π, γ, etc.)	
3. GCR heavy ions	3.1 GCR fragments	

The present analysis includes all particles from classes 1., 1.3, 2., 2.1, 2.1.1, 2.3, 3., and 3.1, which were deemed to dominate the high-LET track detector measurements. Work is underway to examine the significance of the remaining components.

The calculations in this paper are based on the space radiation environment models AP-8 /7/ and CREME /8/. AP-8 contains models of the trapped proton environment in the magnetosphere at solar minimum and solar maximum. CREME contains models of the galactic cosmic radiation proton and heavy-ion environment at solar minimum and solar maximum, as well as codes for transmission of these fluxes inside the magnetosphere. Interpolation is required to determine the environments between the extremes of solar activity. In this analysis, the solar minimum environment is used because of the broad minimum observed from mid-1985 through mid-1986. No significant solar energetic particle events occurred during these missions /9/.

Transport of primary particle species, as well as galactic cosmic ray fragments of all orders, was performed using the UPROP code /10/. Transport of proton-induced secondary particles was performed using the HETC code /11/. Transport was performed for 19 thicknesses of aluminum shielding: 0, 1, 2, 3, 4, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, and 90 g cm^{-2}. A weighted sum of LET spectra based on the average of six shuttle shielding distributions convoluted with astronaut body shielding of the dosimeters (Figure 1) is used for final comparisons with observation.

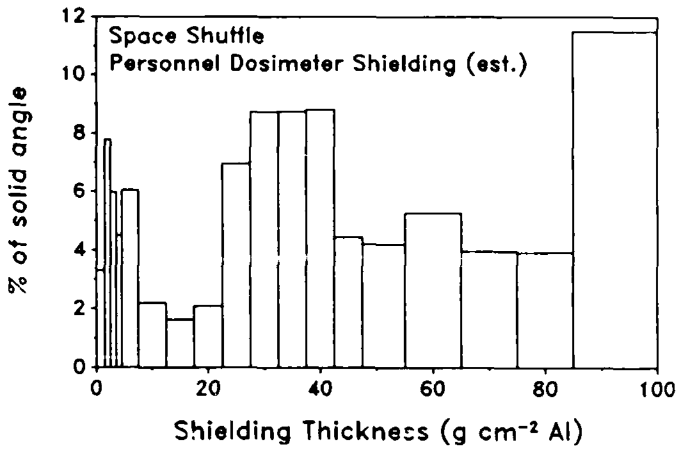

Figure 1: Estimated chest-mounted personnel dosimeter shielding on the Space Shuttle.

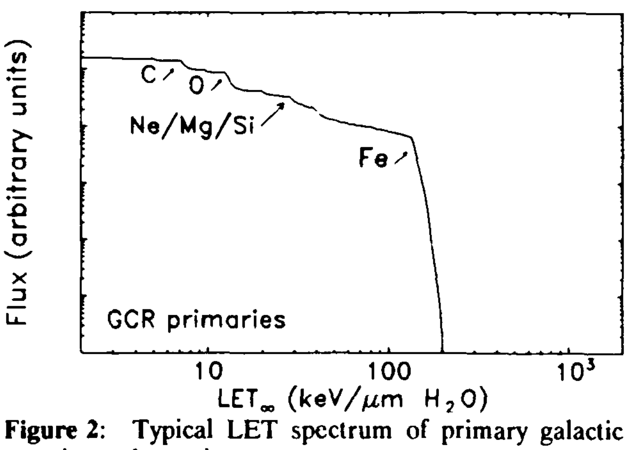

Figure 2: Typical LET spectrum of primary galactic cosmic ray heavy ions.

Typical primary and secondary LET spectra are shown in Figures 2 and 3. The primary LET spectrum (Figure 2) is of the form obtained by Heinrich /12/. It shows discontinuities at the minimum LET of abundant, relativistic heavy nuclei in the GCR. The secondary LET spectrum (Figure 3) shows discontinuities at the maximum LET of stopping recoil nuclei. These nuclei are in the charge interval $2 \leq Z \leq 9$ for a water target. It is noteworthy that all stopping heavy ions can exceed the LET of relativistic iron. It follows that in low-inclination orbits, where geomagnetic shielding prevents non-relativistic cosmic rays from reaching the spacecraft, recoil secondaries may be the only source of particles above ~130 keV/μm. These conditions are expected to occur on the STS-51J and STS-61C flights.

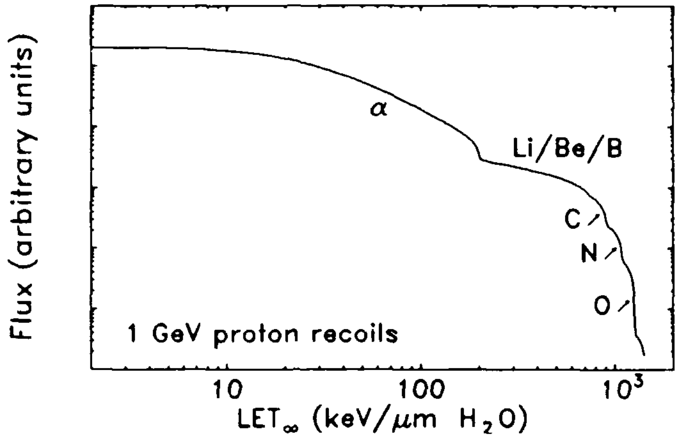

Figure 3: Typical LET spectrum of secondary recoil nuclei from 1 GeV proton interactions.

RESULTS

The results of this analysis are presented in Figures 4, 5, and 6. Each figure shows the 1σ upper and lower limits of the measured LET spectrum (solid lines), the model prediction of the total LET spectrum (dashed line), and the model prediction of the LET spectrum from primaries (dotted line). The difference between the dotted and dashed lines is due to secondary particles from interactions of either cosmic rays or trapped protons.

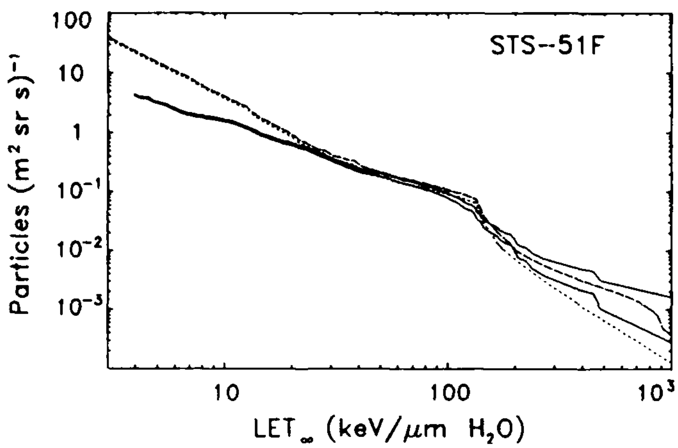

Figure 4: Observed (within solid lines) and predicted (dashed line) LET spectrum of personnel dosimeters on STS-51F. Dotted line shows contribution of primary radiation.

The predicted and observed LET spectra on STS-51F are in excellent agreement above 20 keV/μm. Below 20 keV/μm our predictions gradually deviate above the observations, possibly indicating a loss of efficiency in the track detector. A relatively small secondary contribution occurs above 200 keV/μm, accounting for some improvement in the prediction (above primaries alone). Since the LET spectrum on the high-inclination flight of STS-51F is dominated by galactic cosmic radiation, this comparison serves as a validation of the CREME environmental model and the UPROP transport code.

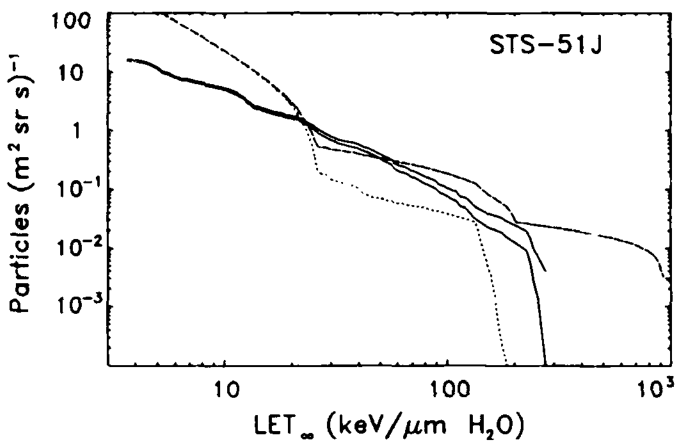

Figure 5: Observed (within solid lines) and predicted (dashed line) LET spectrum of personnel dosimeters on STS-51J. Dotted line shows contribution of primary radiation.

The LET spectrum of the high-altitude flight of STS-51J is dominated by trapped protons and their secondaries. We note that the primary spectrum (dotted line) cannot account for observed particles between 175 keV/μm and 300 keV/μm. The model predicts additional flux above 300 keV/μm which is at the statistical limit of the detector. The secondary alpha contribution between 25 keV/μm and 100 keV/μm brings the prediction into substantially better agreement with the measured spectrum. Several explanations for the poor prediction of spectral shape in this range have been considered including uncertainty in the trapped proton environment, the alpha recoil energy spectrum, and a possible trapped alpha contribution.

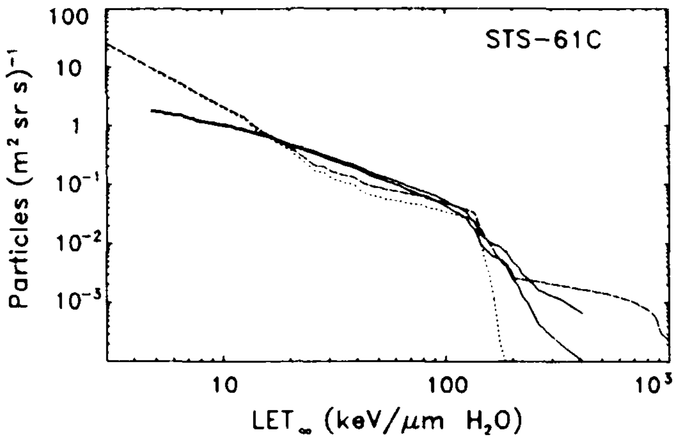

Figure 6: Observed (within solid lines) and predicted (dashed line) LET spectrum of personnel dosimeters on STS-61C. Dotted line shows contribution of primary radiation.

The LET spectrum measured on the low-altitude flight of STS-61C agrees well with model predictions over the entire LET range above 15 keV/μm. As in the case of STS-51J there is clear evidence for a secondary component above 175 keV/μm which cannot be accounted for by primary radiation alone. The model predicts high-LET particles above the statistical limit of the detector (~300 keV/μm).

SUMMARY AND CONCLUSIONS

Model predictions of LET spectra measured in personnel dosimeters on three Space Shuttle flights have been prepared. The predictions include trapped protons, galactic cosmic radiation and its nuclear fragments, and target secondaries. Predictions are in very good agreement with observed spectra above 20 keV/μm. Below that threshold, detector efficiency may be decreasing. Evidence for the secondary component is found in the low-inclination flights of STS-51J and STS-61C where relativistic heavy nuclei cannot account for observed high-LET particles. It is predicted that these recoil nuclei also exist at LET considerably above the current statistical limit of the detector. Longer exposure or greater surface area are necessary to observe these particles.

Our models predict the following doses for the three missions:

STS-51F	0.15 cGy	0.24 cSv
STS-51J	0.74 cGy	0.91 cSv
STS-61C	0.10 cGy	0.13 cSv

The deduced doses for STS-51F and STS-61C are sensitive to the accuracy of the CREME model predictions of lightly-ionizing galactic cosmic ray species at solar minimum. The deduced doses for STS-51J are sensitive to the accuracy of the AP-8 model at solar minimum. Agreement of the high-LET data can be seen in Figures 4, 5, and 6.

ACKNOWLEDGEMENTS

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GALACTIC COSMIC RAYS AND CELL-HIT FREQUENCIES OUTSIDE THE MAGNETOSPHERE

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ABSTRACT

An evaluation of the exposure to galactic cosmic radiation to space travelers outside the earth's magnetosphere is made by calculating fluences of high-energy primary and secondary particles with various charges traversing a sphere of area 100 μm^2. Calculations relating to two shielding configurations are presented: the center of a spherical aluminum shell of thickness 1 g/cm^2, and the center of a 4 g/cm^2 thick aluminum spherical shell within which there is a 30 g/cm^2 diameter spherical water phantom with the point of interest 5 g/cm^2 from the surface. The area of 100 μm^2 was chosen to simulate the nucleus of a cell in the body. The frequencies as a function of charge component in both shielding configurations reflects the odd-even disparity of the incident particle abundances. For a three-year mission, 33% of the cells in the more heavily shielded configuration would be hit by at least one particle with Z greater than 10. Six percent would be hit by at least two such particles. This emphasizes the importance of studying single high-Z particle effects both on cells which might be "at risk" for cancer induction and on critical neural cells or networks which might be vulnerable to inactivation by heavy charged particle tracks. Synergistic effects with the more numerous high-energy protons and helium ions cannot be ruled out. In terms of more conventional radiation risk assessment, the dose equivalent decreased by a factor of 2.85 from free space to that in the more heavily shielded configuration. Roughly half of this was due to the decrease in energy deposition (absorbed dose) and half to the decrease in biological effectiveness (quality factor).

INTRODUCTION

For manned space missions outside the confines of the earth's sheltering magnetosphere, space travelers will be exposed to the fluences of the high-energy primary galactic cosmic radiation plus secondary radiation produced by the primaries as they pass through the shielding of the spacecraft and the "self-shielding" produced by the astronaut's body /1-4/. A standard method of determining the exposure is by calculating the absorbed dose at the point of interest /3,5/. This is done by first calculating the energy and/or LET spectra at the point and performing the appropriate integrations. The presently accepted way of determining the risk at low exposure levels is by determining the dose equivalent /6/. This is done by multiplying the spectra, before integration, by a Quality Factor (Q), which is a weighting factor that is a function of LET /7/ that provides an approximate correction for the increased biological effectiveness of the higher LET components by giving them more weight than the low LET components. This methodology has been applied to the assessment of astronaut dose equivalents for Space Station orbits /8/, on the lunar surface /9/ and on a manned Mars mission /10/.

It has been pointed out, however, that the frequency of heavy-ion traversals is very low outside the earth's magnetosphere /11/ and that the probability of two particles traversing an area the size of a cell nucleus (100 μm^2) is extremely low. Therefore, biological effects of importance (molecular events in the DNA such as deletions, translocations, and other rearrangements in the chromatin) that may lead to neoplastic transformation of the hit cell may well be initiated by single track traversals of the cell nucleus. It is reasonable then to calculate the frequencies of such hits to a cell nucleus produced by the various components of the galactic cosmic radiation so that an approach to risk assessment may eventually be made based on particle fluences rather than absorbed dose. This or similar suggestions have been made in the past /12,13/; and, in this paper, examples of fluences of the heavy component of the galactic cosmic radiation are calculated behind two representative shielding configurations as a first step in such a revised risk assessment process.

DESCRIPTION OF THE TRANSPORT CALCULATION

The fluence calculations in this paper were performed using the transport code UPROP /14/ and the most recent CREME galactic cosmic ray environment /15/. The calculation begins with energy spectra of elements with atomic number between 1 and 28 (hydrogen through nickel) in the energy range from 1 MeV/nucleon to 100 GeV/nucleon. The spectra are approximated by logarithmically-spaced grid of 500 energy points per elemental species. Fluences at solar minimum (galactic cosmic-ray maximum) with no solar activity are specified.

The transport code provides an exact numerical solution of the one-dimensional continuity equation taking into account both ionization losses and nuclear fragments. Ionization losses are treated in the "continuous-slowing-down approximation." Nuclear fragmentation processes are treated in the "straight-ahead approximation" which assumes that fragments are created with the same velocity as their progenitors after a nuclear interaction and maintain the same direction.. All orders of fragments (secondaries, tertiaries, etc.) are followed in the calculation.

The monodirectional particle fluences are transported through one-dimensional layers of material. Two shielding configurations (Cases a and b) are considered in this study. Case a is obtained by transport through 1 g/cm^2 of aluminum. Case b is obtained by transport through 4 g/cm^2 of aluminum, then variable thicknesses of water (from 5 cm through 25 cm). In Case a, the result is multiplied by 4 π to obtain the fluence expected at the center of a 1 g/cm^2 aluminum spherical shell (Figure 1a) in an isotropic radiation field. In Case b, appropriately weighted calculations are summed to obtain the fluence at 5 g/cm^2 depth in a 30 g/cm^2 diameter water phantom which is inside a 4 g/cm^2 aluminum shell (Figure 1b).

Conventional procedures /6/ are used to convert fluences into LET spectra, and to obtain the radiation dose, dose equivalent, mean quality factor, track-averaged LET, and dose-averaged LET.

HIT FREQUENCIES FOR EACH Z COMPONENT

The results of the calculations for cases a and b are presented in Figure 2. The intensities for the various Z components are given in terms of the number of traversals through a 100 μm^2 area at the point of interest during a three-year mission occurring at solar minimum. This period was chosen for two reasons. First, it is a typical mission length that has been suggested for a trip to Mars. Second, it is the interval in the eleven-year solar cycle during which galactic cosmic radiation is at maximum intensity. Any risk outside the magnetosphere from radiation is dominated by the galactic component, since large solar particle events are absent during this interval of solar inactivity. The 100-μm^2 area was chosen as a representative cross section of the nucleus of a cell within the body. Such frequencies of hit cell nuclei may determine to a large extent the probability of neoplastic transformation and the ultimate rate of radiation-induced cancer

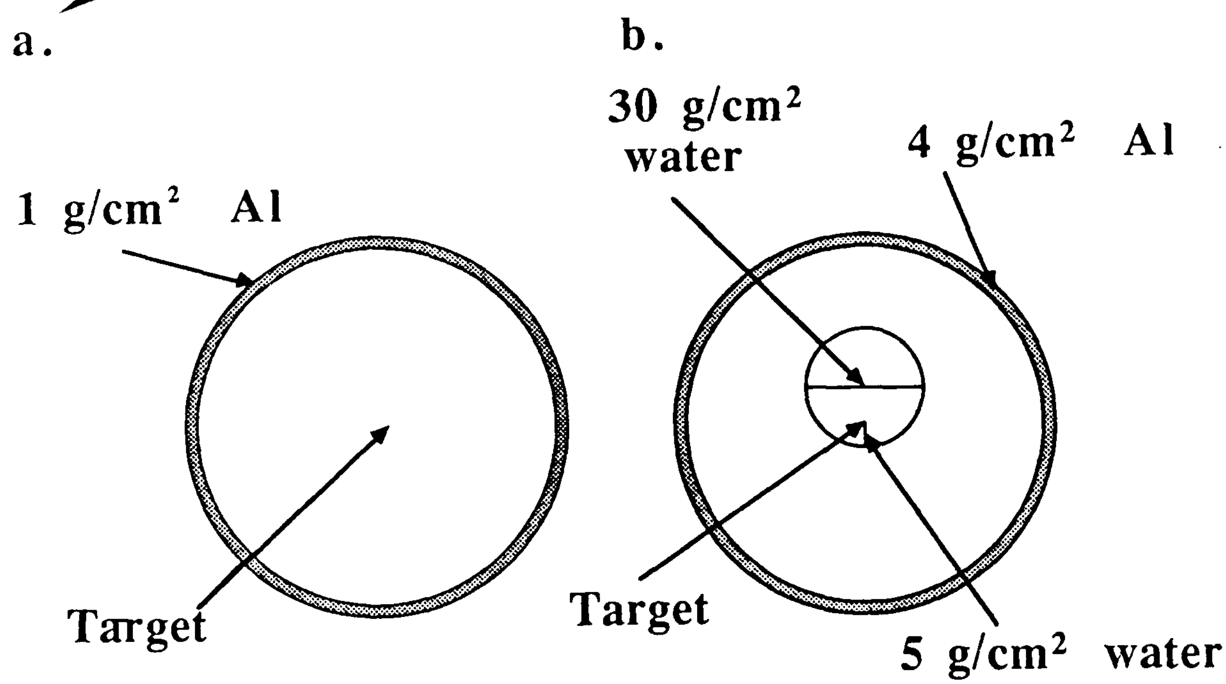

Fig.1. The geometry of the two shielding configurations studied in this paper. Case a: the point of interest is the center of an aluminum spherical shell with a 1 g/cm^2 thickness. It is assumed that the areal density (distance in g/cm^2) from the inner surface of the shell to the point of interest is negligible compared to the shell thickness. Case b: the point of interest is the center of an aluminum spherical shell with a 4 g/cm^2 thickness and 5 g/cm^2 from the surface of a 30 g/cm^2 diameter spherical water phantom.

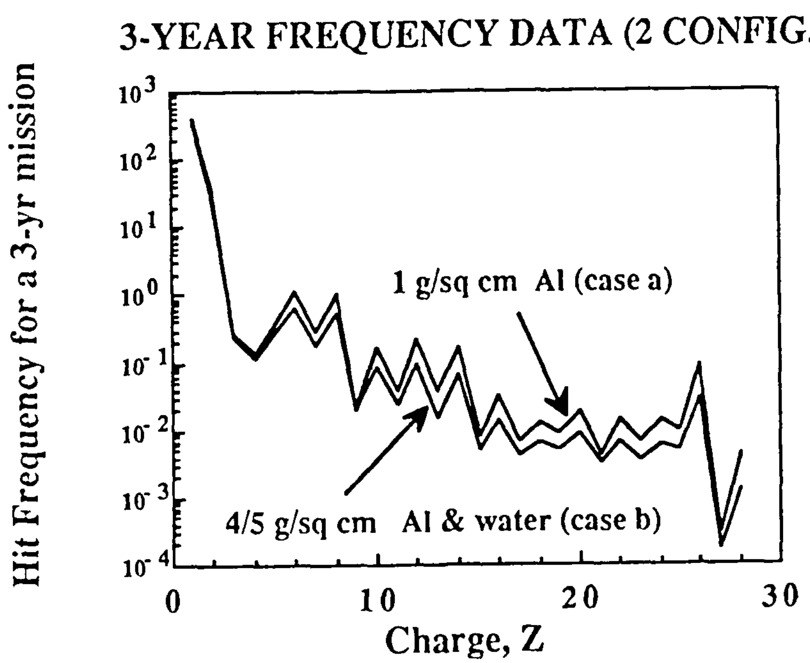

Fig. 2. Frequencies of hits from galactic cosmic rays and secondary fragments in a 100 μm^2 area at the point of interest in the two shielding configurations (Cases a and b) studied in this paper as a function of the charge of particles at the point calculated for a 3-year mission outside the geomagnetosphere at solar minimum.

resulting from these missions. In addition, neural networks and/or cells might be affected by hits of such heavy particles. Thus, future study of the mechanisms of neoplastic transformation and the carcinogenic process and/or neural damage as caused by single high-LET charged particle tracks may well give us a more scientific basis than now exists to predict cancer incidence from the low exposures that will be received during such missions outside our magnetosphere.

We note in Figure 2 that the characteristic odd-even charge variation in frequencies, which is also strongly evident in the free space measurements, can be seen for both shielding configurations. This implies that for these shielding thicknesses, the fragmentation of the higher Z components does not drastically change the overall mix of particles. Thus, although the particles are undergoing nuclear fragmentation within the shielding, it is not occuring to such an extent that the initial odd-even disparity between charge components is lost. The variation in shielding between the Case a and Case b configuration, however, causes a factor of two variation in hit frequences from the higher Z components.

It is also clear from Figure 2 that these heavy particle fluences occur in conjunction with much higher fluences of high energy protons and helium ions. For both shielding configurations, the proton fluence is roughly one every three days and the helium ion fluence is roughly one every month through a cell nucleus. These particles make up a significant fraction of the conventional absorbed dose. Presently, we cannot rule out the possibility that there may be a synergistic effect between a heavy particle traversal and the more frequent traversals from these low LET components.

RISK OF TWO OR MORE TRAVERSALS

There is evidence that the risk of cell transformation depends not only on the LET of the particles in the radiation field, but also on the time course of radiation delivery /16 - 18/. Transformation probability from high LET radiation has been seen to have a different dependence on dose rate than that from low LET radiation. Some experiments show an enhanced transformation if the high LET radiation is given in a protracted schedule. It is of some interest, then to determine the probabilities of two or more traversals through any given cell nucleus during the course of a mission. With the assumption of a Poisson probability distribution for the spatial distribution of the particles, the frequencies for two or more hits/nucleus can be calculated. The results are shown in Table I for the two shielding configurations (Cases a and b) chosen for this study. The galactic radiation was split into several charge groups for convenience. The percentage of cell nuclei hit by one or more and by two or more particles is given for each charge group for one year and for a three-year mission at solar minimum. Note that because of the properties of the Poisson distribution, the percentages for a three-year mission are not simply three times the one year percentages. We see from the table that for one year, the probability of a cell nucleus being hit by more than one particle with Z between 10 and 28 is not high (3% for Case a and 0.8% for Case b). However, for a three year mission, these probabilities rise to 21% and 6%, respectively. In the above, we have assumed that the cell in question has remained viable in the body throughout the mission duration. If cells living a shorter time in the body are also at risk, their lifetimes will also play a role in the calculation, and the probability of their being hit will be correspondingly less.

It in interesting to note that for a three-year mission, even at the more heavily shielded position (Case b), 33% of cell nuclei will be hit by at least one particle in the range of Z from 10 to 28.

TABLE I: Percentage of Cell Nuclei (area=100 μm^2) Hit in Two Shielding Configurations

	Case a: 1 g/cm^2 Spherical Al Shell				Case b: 4 g/cm^2 Spherical Al Shell plus 5 g/cm^2 in a 30 g/cm^2 Diameter Water Phantom			
	One Year		Three Years		One Year		Three Years	
Charge Group	≥1 Hit	≥2 Hits	≥1 Hit	≥2 Hits	≥1 Hit	≥2 Hits	≥1 Hit	≥2 Hits
3-9	65	28	96	82	49	14	86	59
10-16	20	2.1	48	14	10	0.51	27	4.0
17-25	3.1	0.05	9.2	0.43	1.6	0.001	4.8	0.12
26-28	2.9	0.04	8.6	0.38	0.99	0.005	2.9	0.04
10-28	24	3.2	57	21	12	0.8	33	6.0

COMPARISON WITH OTHER RADIATION RISK ASSESSMENT PARAMETERS

Absorbed doses, dose equivalents, average quality factors, and dose- and track-averaged LETs have also been calculated for these shielding configurations. They are shown in Figure 3 along with results for spherical aluminum shells of 0, 5, and 10 g/cm^2 radii for comparison. We note that the more complicated geometry of Case b provides more effective shielding than 10 g/cm^2 of aluminum, and may supply as much effective shielding as 15 to 20 g/cm^2 of aluminum. We also note that there is very little variation of these parameters throughout the shielding region studied, and with the exception of the dose-equivalent and dose-averaged LET, they vary by less than a factor of two. From free space to Case b, the dose equivalent and dose averaged LET varies by factors of 2.85 and 4.48, respectively. The decrease in the dose equivalent between free space and Case b is made up roughly equally between the decrease in absorbed dose and the decrease in the quality factor.

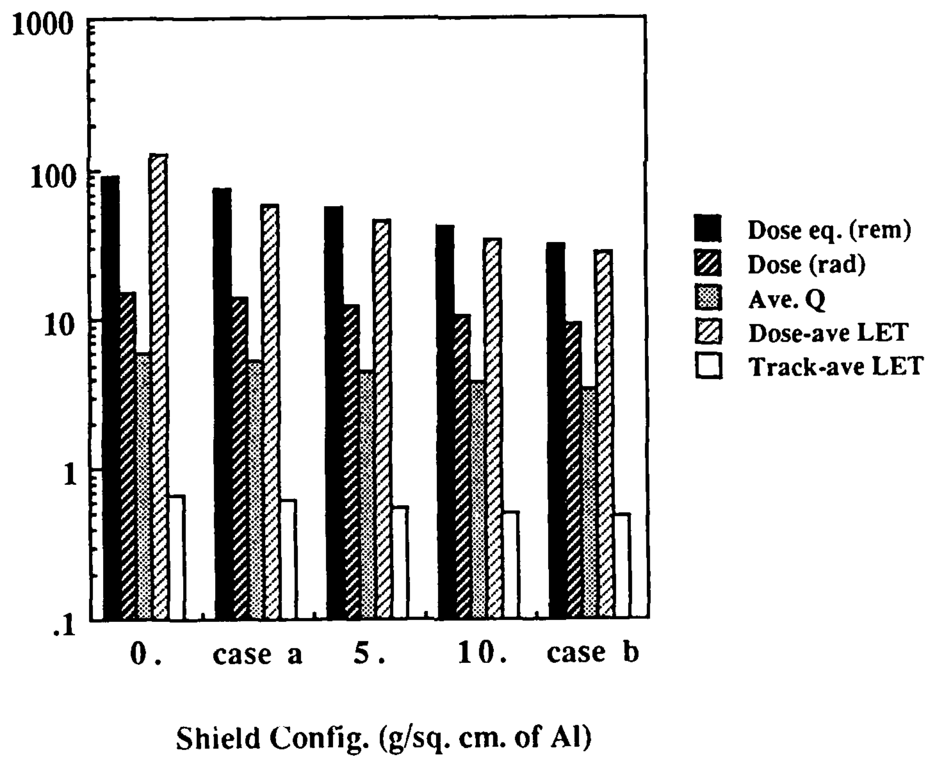

Fig. 3. The dose equivalent (in rem), absorbed dose (in rad), average quality factor, and dose- and track-averaged LET's (in keV/μm) calculated at the center of aluminum spheres with thicknesses 0, 5, and 10 g/cm^2 are compared with these quantities calculated for Cases a and b.

CONCLUSIONS

We have studied two shielding configurations to determine the variation of various radiation exposure parameters which may be useful in understanding the effects of shielding on the attenuation of the galactic cosmic radiation on missions undertaken during solar minimum. In particular, the frequencies of cell nuclei hit have been calculated. For the most heavily shielded dose point, 33% of the nuclei will be hit by at least one particle with Z between 10 and 28 during a three-year mission. Six percent will be hit by two or more such particles. Thus, single high-LET track effects are extremely important. However, for missions as long as three years, multiple traversals of nuclei of very long-lived cells by two or more high-LET tracks cannot be neglected.

Finally, we see the extent to which the exposure from galactic cosmic rays is attenuated with additional shielding. In particular, with 4 g/cm^2 of aluminum and an additional 5 g/cm^2 inside a 30 g/cm^2 diameter water phantom, the dose equivalent is decreased by a factor of almost 3 from the free space dose equivalent. Roughly half of this decrease comes from the decrease in absorbed dose (the energy deposited per gram) and half from the decrease in biological effectiveness (the "quality" of the radiation). These conclusions are based on the traditional methods used in the field of radiation risk assessment. In the future, new methods utilizing quantities such as the hit frequences calculated here coupled with mechanisms and/or models of the carcinogenic process and perhaps a better knowledge of the effects of these particles on neural cells or networks may give us a more confident estimation of the risk of radiation exposure on long term missions.

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